Superconducting at Radio Frequencies

University of D0
Leo Bellantoni
April 2011

Program

- Disclaimer of veracity
- Gratuitous advertisements
- About RF cavities
- About superconductivity
- Basic design considerations
- Some pictures

Disclaimer

I stopped being heavily engaged in the SRF field 2 or 3 years back

Some interesting things have happened since then

But I don't really know much about them

So I won't tell you about them!

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SRF 2011

Dear Colleagues,

We welcome you to attend the 15th International Conference on RF Superconductivity to take place on July 25-29, 2011 in downtown Chicago. Our goal is to continue in the tradition of the 14 previous conferences and provide a lively forum for SRF scientists, engineers, students and industrial partners to present and discuss the latest developments in the science and technology of superconducting rf for particle accelerators.

Tutorial sessions preceding the conference will be held from July 21-23 at Argonne National Laboratory in the Chicago suburbs.

Registration is now open. Please register as soon as possible.

You can register online by clicking on the following link:
https://ppdconf.fnal.gov/SRF11/SRF11_Registration.htm

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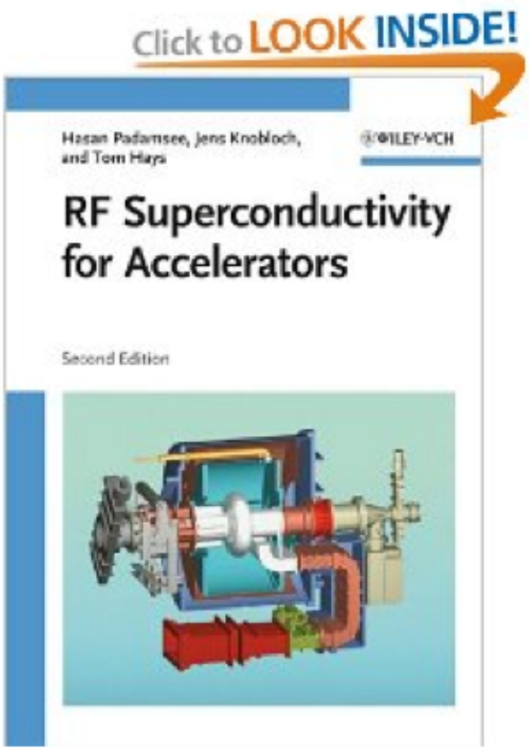

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RF Superconductivity for Accelerators [Hardcover]

Hasan Padamsee (Author), Jens Knobloch (Author), Tomas Hays (Author)

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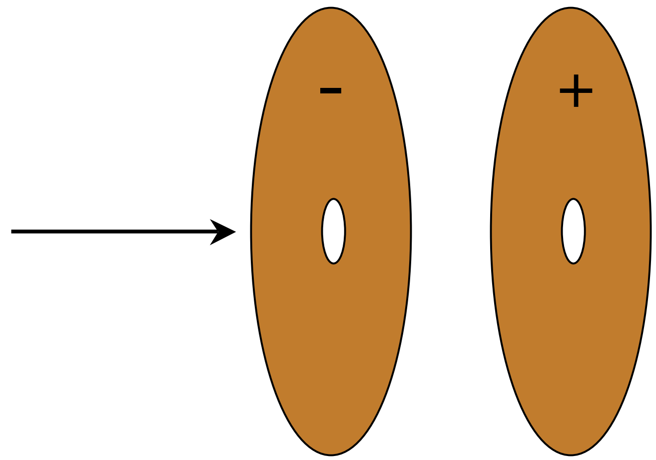
The pillbox cavity

To make a subatomic particle move at nearly the speed of light you … *push it!*

Usually with an electric field. An electric field that switches on and off quickly will not cause sparks, corona, or other electric discharge at field levels that cause such things in a steady state.

But the beam must be in a vacuum ⇒



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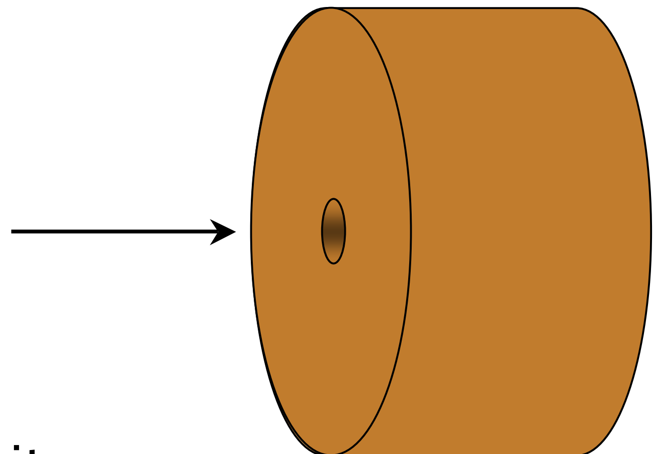


But the beam must be in a vacuum ⇒

the pillbox cavity

The pillbox cavity

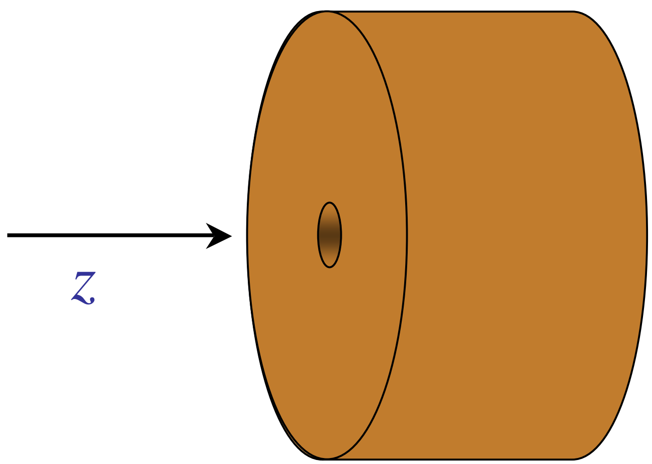
Boundary conditions and the Maxwell Equations constrain 5 of the 6 quantities $\{Ex, Ey, Ez, Hx, Hy, Hz\}$

I'll use Ez as the single scalar to solve for in the r–ϕ plane.

$$\left(\nabla_\perp^2 + \gamma_j\right) E_z = 0$$

Poisson's equation

γ_j is an eigenvalue



The pillbox cavity

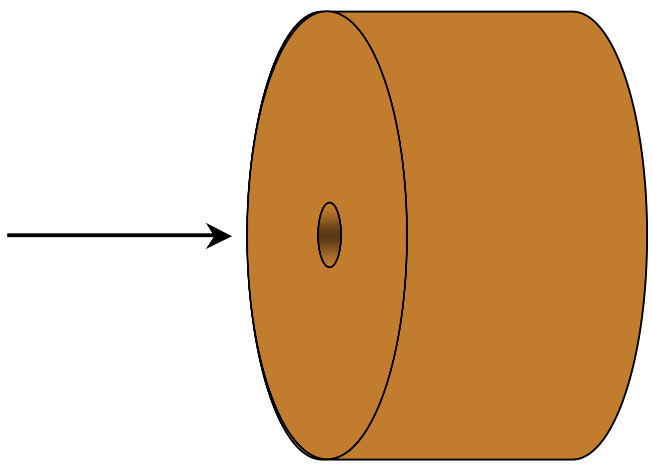
Boundary conditions and the Maxwell Equations constrain 5 of the 6 quantities $\{Ex, Ey, Ez, Hx, Hy, Hz\}$

I'll use Ez as the single scalar to solve for in the $r\!-\!\phi$ plane.

$$\left(\nabla_{\perp}^{2} + \gamma_{j}\right) E_{z} = 0$$

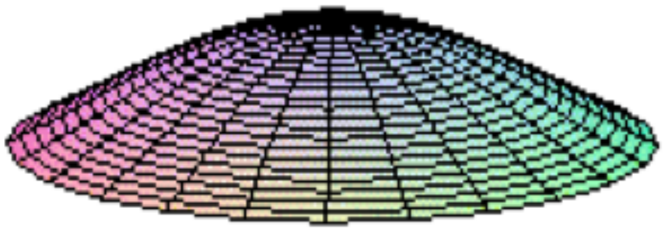
Poisson's equation

You know this problem!



The pillbox cavity

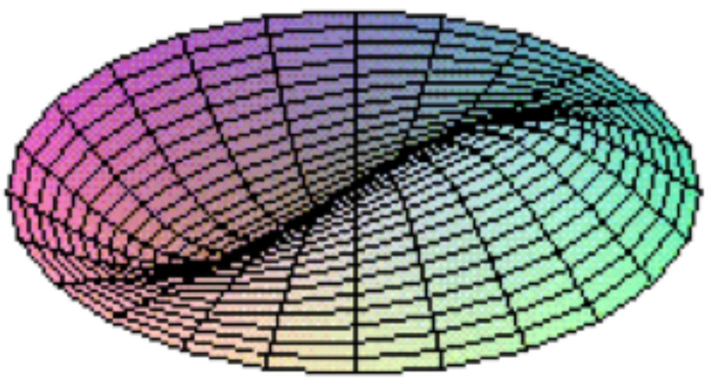
The fundamental mode



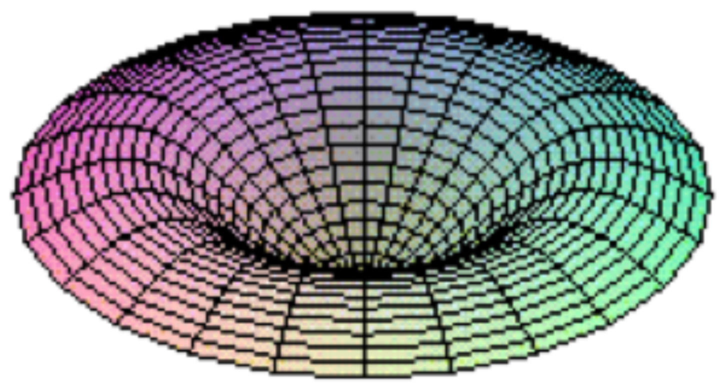
TM_{010}

Magnetic circulation in plane perpendicular to the beam axis

Higher order modes



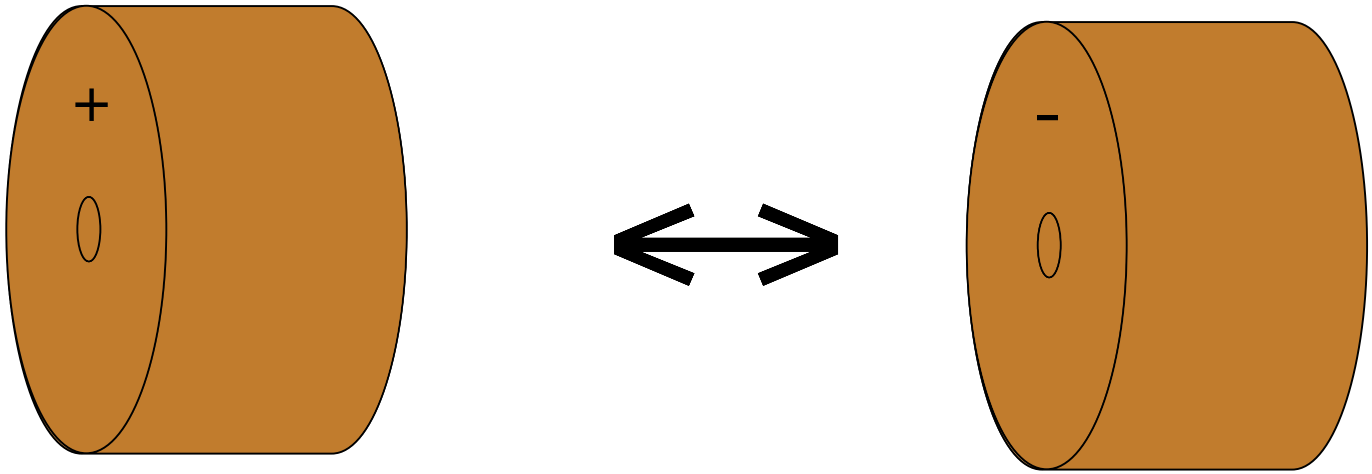
TM_{110}



TM_{020}

Even with non-pillbox cavities, solutions "like" these will often occur

Surface currents



Because E_z field oscillates, there are currents on the interior walls of the cavity alternating at the same frequency. They dissipate power

$$\frac{dP}{dA} = \frac{1}{2} R_S \left|\vec{H}\right|^2$$

H in A/m
R in Ω

Surface resistance R_S determined by conductivity and skin depth δ_S; for copper, $R_S \approx 2.61 \times 10^{-7} (\Omega/s^{1/2}) \sqrt{f}$ and $\delta_S \approx 6.61 \times 10^{-3} (m\text{-}s^{1/2}) / \sqrt{f}$

Figures of merit

The power dissipated is proportional to U, the energy stored

$$Q_0 = \frac{\omega_0 U}{P_{WALL}}$$

the "quality"

basically 2π times the number of oscillations it would take to run the resonator down if only power loss is surface currents.

$Q >> 1$ means you can store a lot energy in the cavity easily

For the optimal pillbox cavity, $Q = 257\Omega \,/\, R_S$ – so for a Cu cavity with f on the order of a GHz, Q is on the order of a few 10^4

The increased energy of an electric charge as it passes through the cavity, V_C, goes as $\sqrt{U}$ or equivalently as $\sqrt{P}$

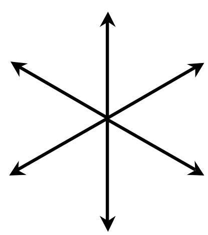
$$R_A \equiv \frac{V_C^2}{P_{WALL}}$$

the "shunt impedance"

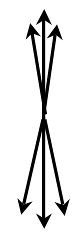
For the optimal pillbox cavity, $R_A = 196\Omega$
Bigger is better

Wakefields

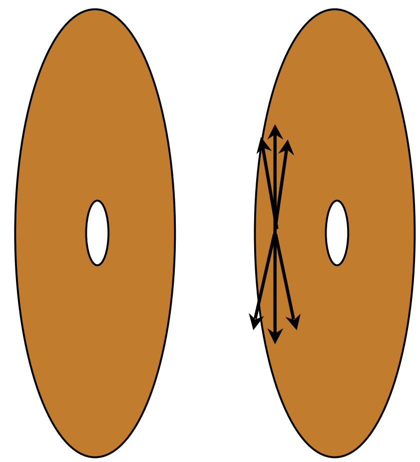
What we are doing is flinging a pancake through a hole in a wall
(the wall is designed to reflect pancake)



The bunch
at rest



The bunch
at $\beta \approx 1$



The bunch at $\beta \approx 1$
about to hit a mirror
with a hole in it

Wakefields

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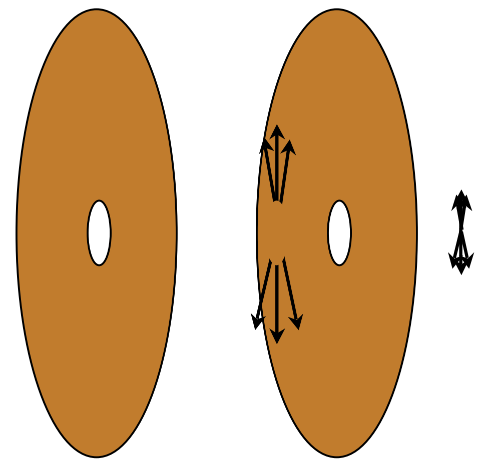


Some of the bunch went through the hole and some was reflected back into the cavity

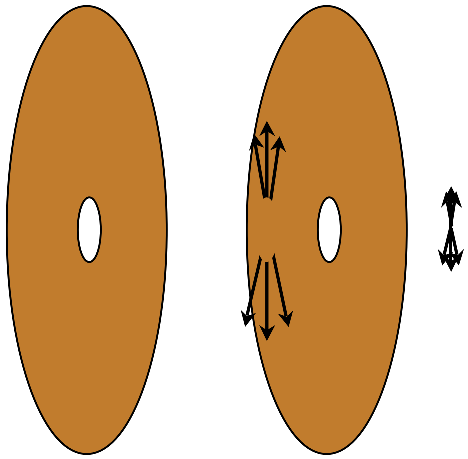
Wakefields

What we are doing is flinging a pancake through a hole in a wall (the wall is designed to reflect pancake)

Now you have some EM fields bouncing around inside that cavity

The higher-frequency part can come back out the hole & down the beampipe

The lower-frequency part will coalesce into the resonant modes of the cavity and hang around to exert annoying forces on the next bunch - that is called a wakefield



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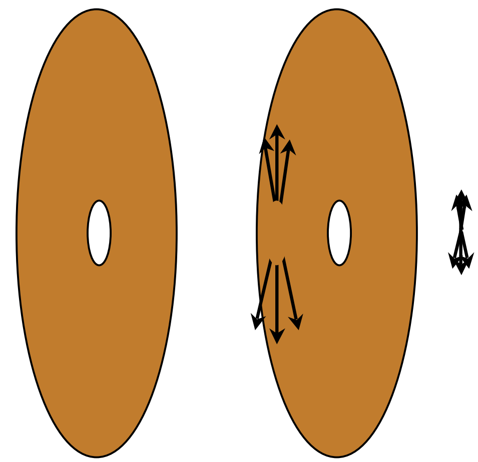

Some of the bunch went through the hole and some was reflected back into the cavity

Small hole
High Q
Bad wakefields

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Superconductivity

- In metals, heat and electrical current are carried mostly by free electrons which (sort of) bounce around in a gas
- As the temperature is lowered, the mean free path of the electrons increases because there are fewer phonons, so thermal and electrical conductivity rise
- Except in some metals, at a certain temperature, the thermal conductivity begins to drop and the (DC) electrical conductivity goes to zero
- From the drop in thermal conductivity, you guess that the electrons are going out of the sort-of-gas and going into some other state which can't possibly be described in a classical mechanical way
- So… write a complex wave function ψ for whatever state it is that the electrons are going into

$$V\psi + \frac{1}{2m}\left[-i\hbar\nabla + q\vec{A}\right]^2\psi = 0$$

But what is V ?

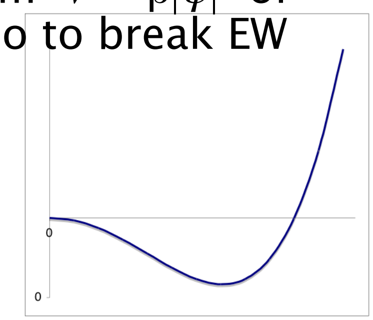
Superconductivity

- The number density of this superconducting stuff ψ, whatever it is, will be $|\psi|^2$ and the potential energy density will be $V|\psi|^2$

- To make superconductivity appear (i.e. to make non-zero ψ) the energy density $V|\psi|^2$ goes negative for non-zero ψ. So use some term $V = -\alpha$ where α depends on temperature and is positive for $T < T_C$ but zero otherwise

- But $-\alpha|\psi|^2$ goes off to $-\infty$ for arbitrarily large $|\psi|^2$ which would mean that all the electrons immediately go into the SC state when $T < T_C$ – but that does not happen. There is still some thermal conductivity left.

- So need to make the potential rise for large $|\psi|^2$ – add a term $V = \beta|\psi|^2$ or energy density = $-\alpha|\psi|^2 + \beta|\psi|^4$ (The same sort of thing we do to break EW symmetry with the scalar Higgs potential)



- Current flow same as standard Shröedinger formalism (although we don't know what exactly is flowing or what charge it has)

Superconductivity

$$\left[-\alpha + \frac{\beta}{2}|\psi|^2\right]\psi + \frac{1}{2m}\left[-i\hbar\nabla + q\vec{A}\right]^2\psi = 0$$

The Ginzburg-Landau theory of 1950

$$\vec{J} = \frac{-iq\hbar}{2m}\left[\psi\nabla\psi^* - \psi^*\nabla\psi\right] - \frac{q^2}{m}|\psi|^2\vec{A}$$

The GL theory is macroscopic both in the sense that ψ is macroscopic (a superconductor can be meters across - but also in the sense that ψ is not explained in terms of more fundamental particles.

Explanation in terms of particle constituents of the metal was done by Bardeen, Cooper and Schrieffer in 1957 - it isn't a simple model.

Ginzberg-Landau Results

Things that can be learned from the GL model:

1. ψ does not have an infinitely sharp transition at the normal/superconducting boundary. Even if it did, ψ does not carry an infinite current density on the surface. Hence, there will be some power-dissipating normal conduction current on the surface (for Nb, within the first 100nm)
2. When there is an externally applied field, currents appear that completely cancel the magnetic field inside the superconducting material – but this adds an energy density $\mu_0 H^2/2$ and when H becomes too high, $(V|\psi|^2 + \mu_0 H^2/2)$ goes positive and the existence of ψ becomes perilous.
3. Depending on the material, superconductivity might just disappear, or magnetic flux lines can enter in a quantum discrete units. Either way, normal electrical resistance appears.

Ginzberg–Landau Unresults

Things that can't be learned from the GL model:

1. Power dissipation from normal conduction on the surface has

$$R_S = A_S\,\omega^2 \exp\left(-\Delta/kT\right) + R_0 \approx n\Omega$$

   Note: (a) advantage of lower frequencies (b) Boltzman factor type temperature dependence of non-Cooper pair density (c) ad-hoc R_0 term.

2. Time for a magnetic fluxoid to enter is $\mathcal{O}[10^{-6}]$ sec; RF field oscillations are $\mathcal{O}[10^{-9}]$ sec. It is possible to exceed H_C up to a certain point, but not by a huge factor.

3. $H_C \approx H_C(0)\,[\,1-(T/T_C)^2\,]$ and $H_C(0) \propto T_C$.

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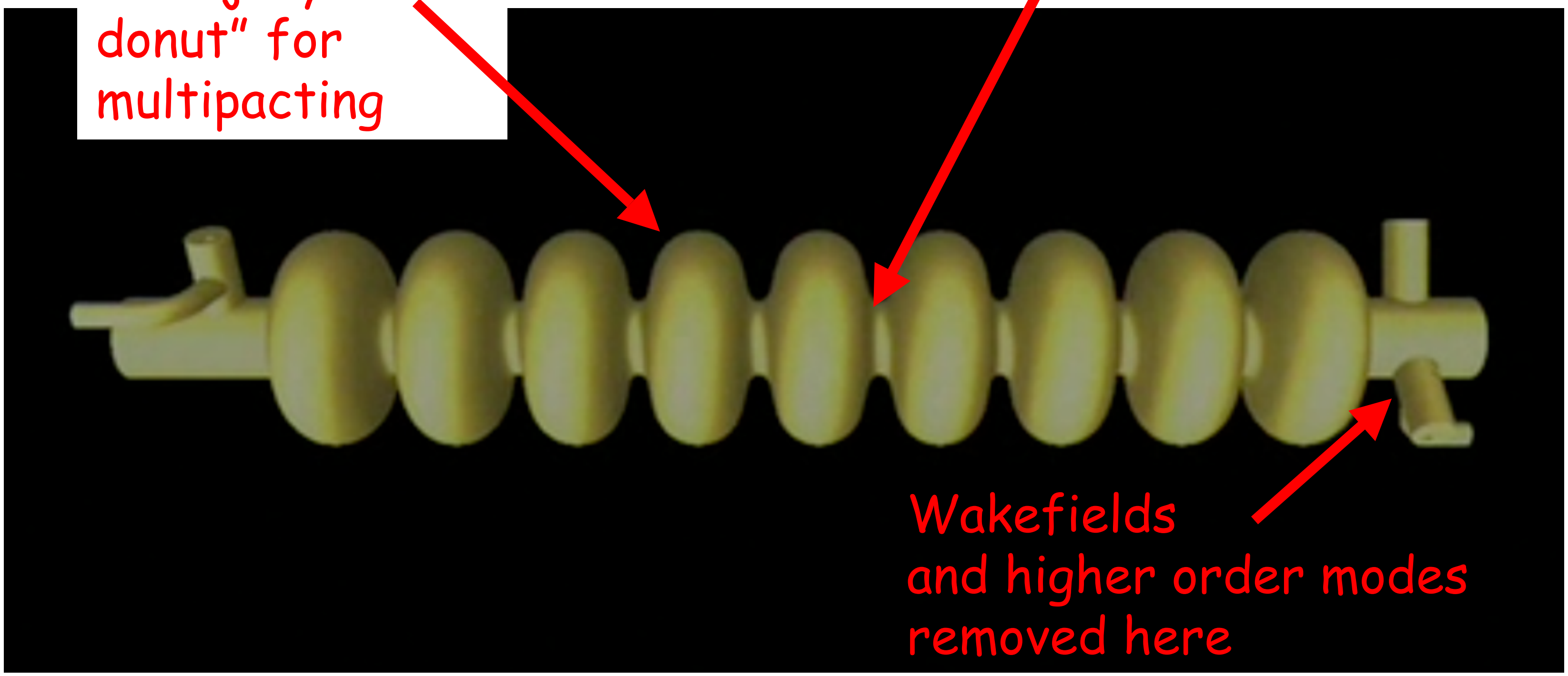
Basic design considerations

- 1TeV collider out of Cu pillboxes at 11.4GHz and 70MV/m (NLC-type numbers) has heat load is 8.4TW for steady-state running
- In real life, Cu structures are either relatively low power or pulsed with very small duty factors
- Superconducting structures are better choice for long bunch trains / higher duty factors
- But high Q and long bunch trains means potentially high wakefields - better to have large apertures between cells for less wakefield creation and to expedite wake energy propagation out the beampipe

Basic design considerations



All this goes into a vessel that holds the LHe
Along with several other devices . . .

Basic design considerations

From $H_C \approx H_C(0)\,[\,1-(T/T_C)^2\,]$

and $H_C(0) \propto T_C$

you want a high-T_C material. Structure shapes can be complicated and so brittle ceramics or alloys / stochiometric mixes that require precise ratios are not usable (so far)
Elemental metal with highest T_C: Niobium - very pure!

Pure Nb is very soft $\Rightarrow$ hard to build very large structures
Welding melt zone a few mm $\Rightarrow$ hard to build very small
Typical operating frequencies are in the range of 1GHz

Basic design considerations

A history of peak field limitations

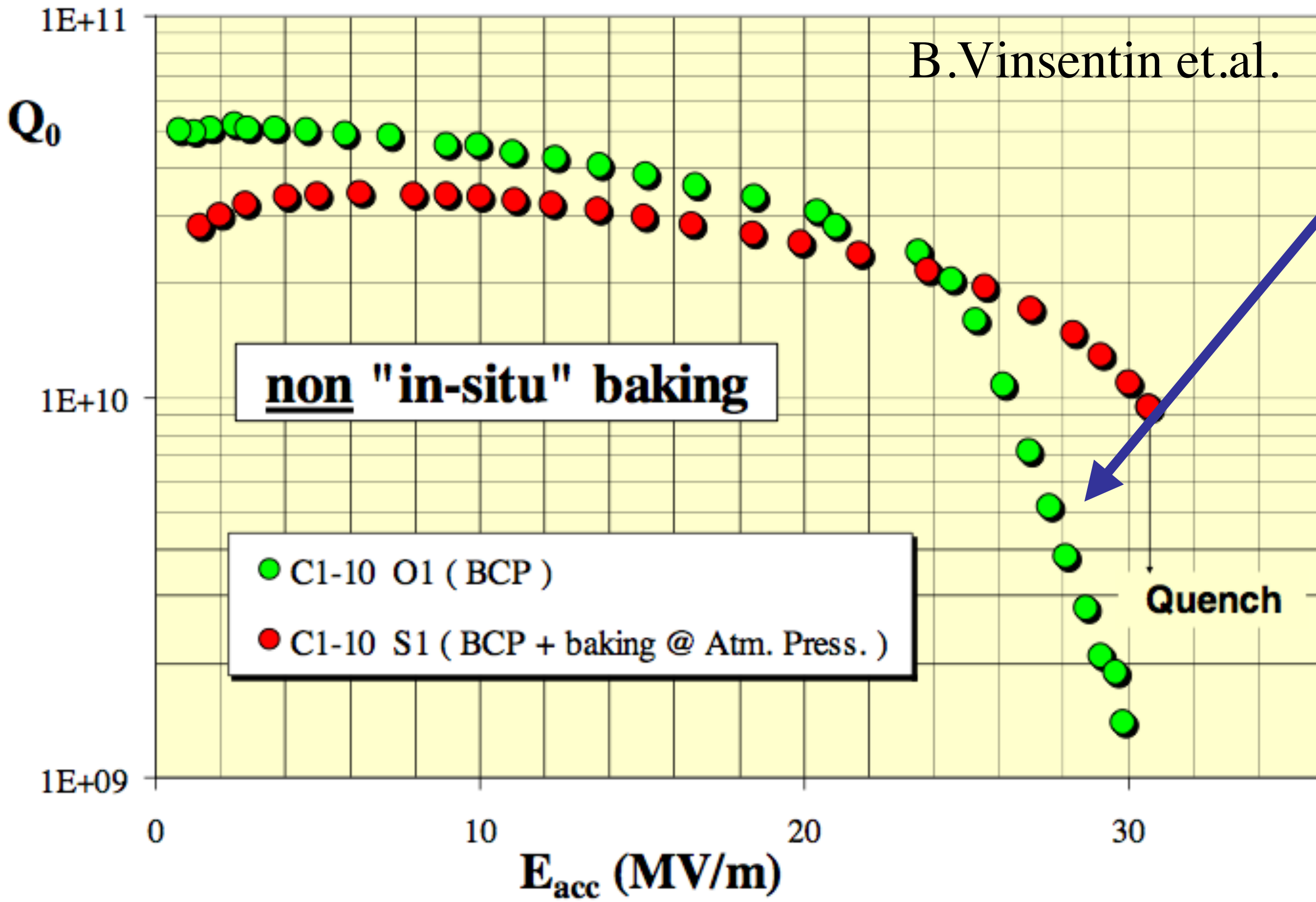
1). Multipacting: electrons from surface are accelerated by RF field and then smash back onto surface thereby liberating more electrons. Cure is to design the shape so this doesn't happen

2). Thermal breakdown: a small spot becomes hot and causes a quench. Cure is careful construction to keep foreign materials out and to use extremely pure Nb for best possible thermal conductivity

3). Field emission: Particles on scale of 1μm stream electrons into the cavity. Cure is high-pressure rinse with ultrapure water and burning the emitters off by running at high power levels

Basic design considerations

Peak field limitation today:



Some cavities do this

Some cavities don't

Nobody knows why

120 C HV bake for 48 hours usually fixes it

From BCS / GL theory, H_C should permit $E_{ACC} \sim 55$MV/m

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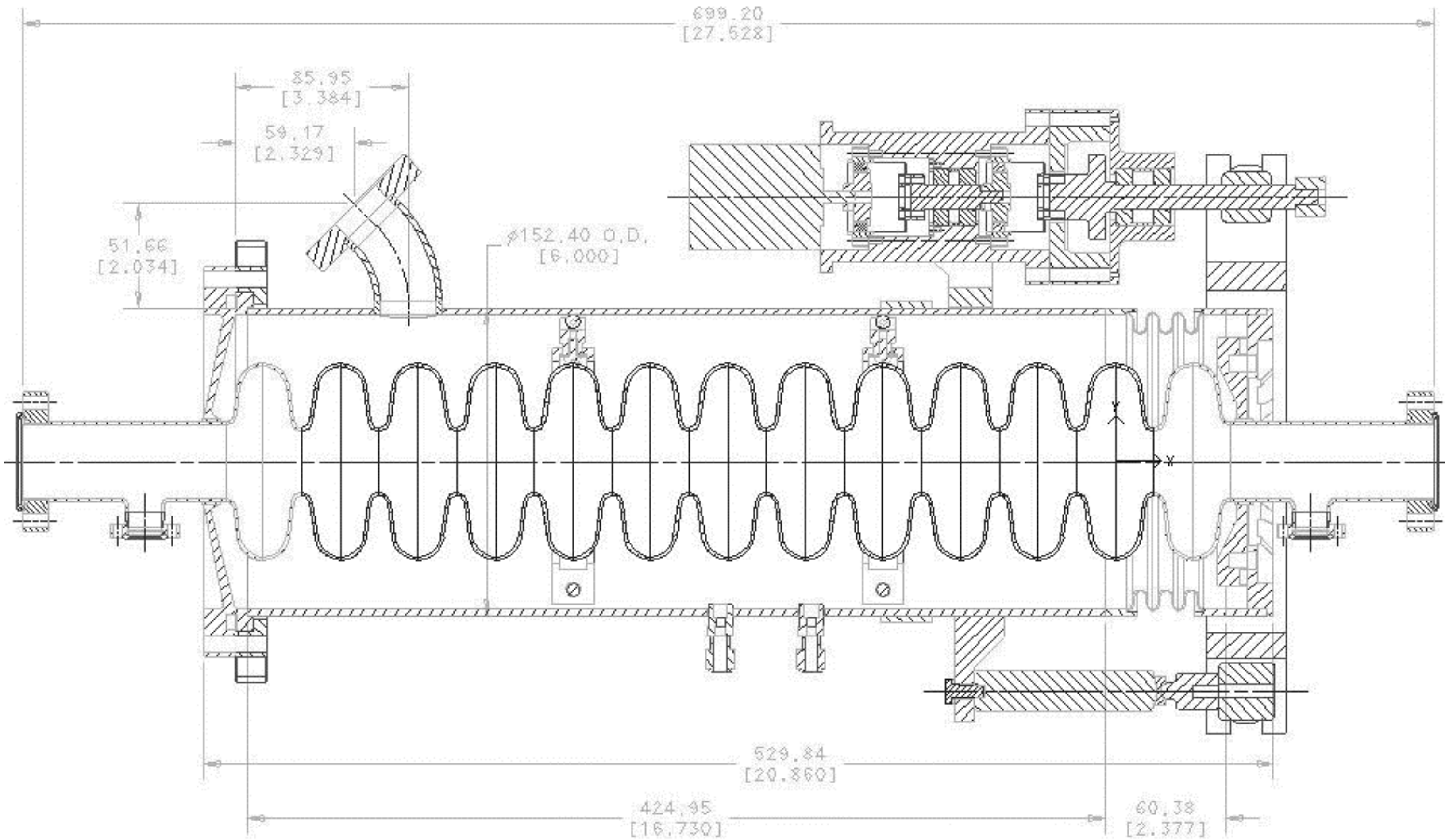

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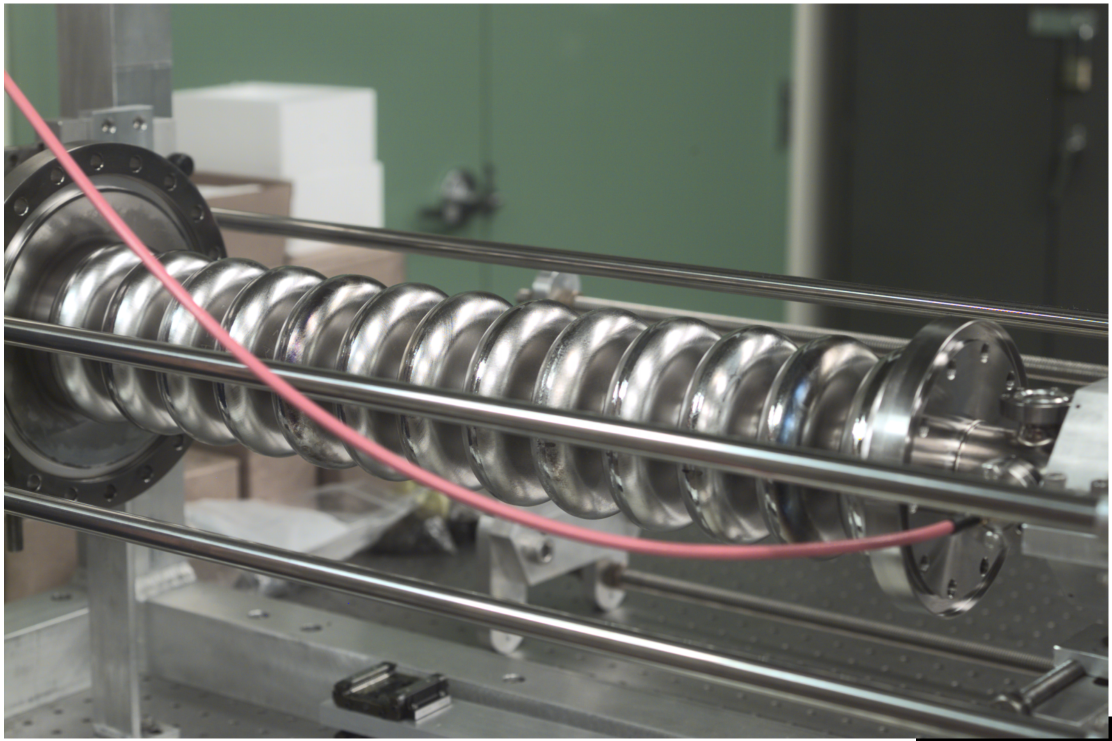

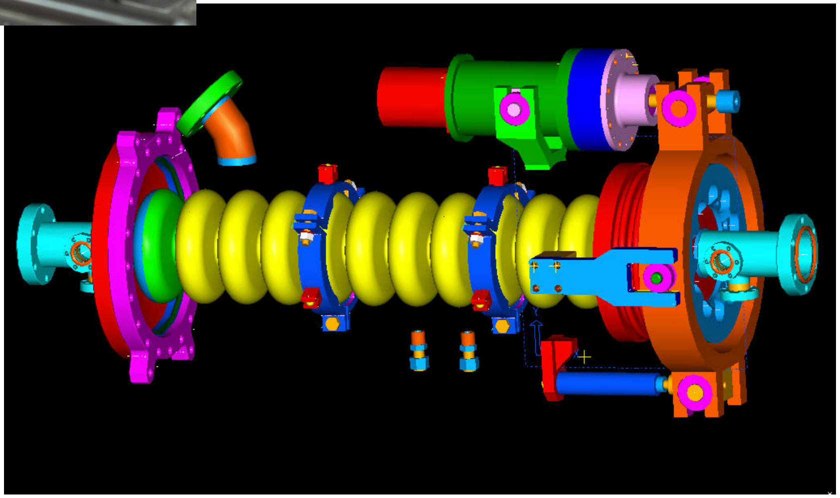

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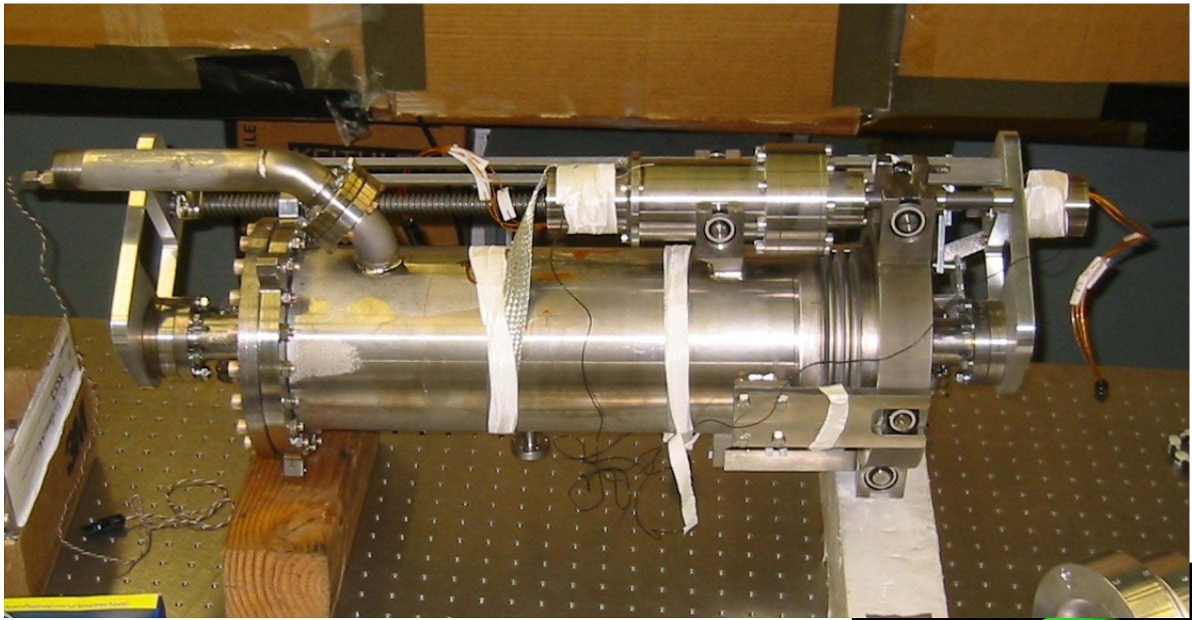
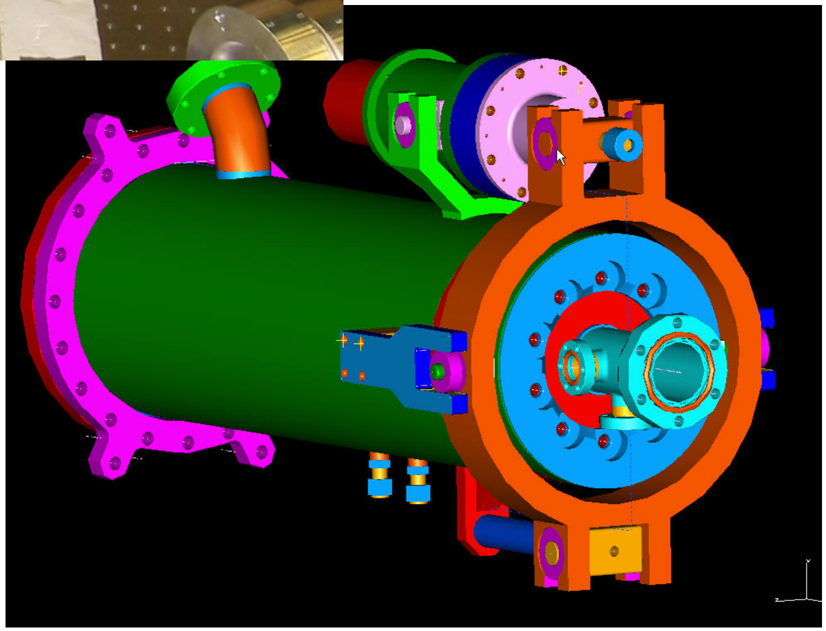
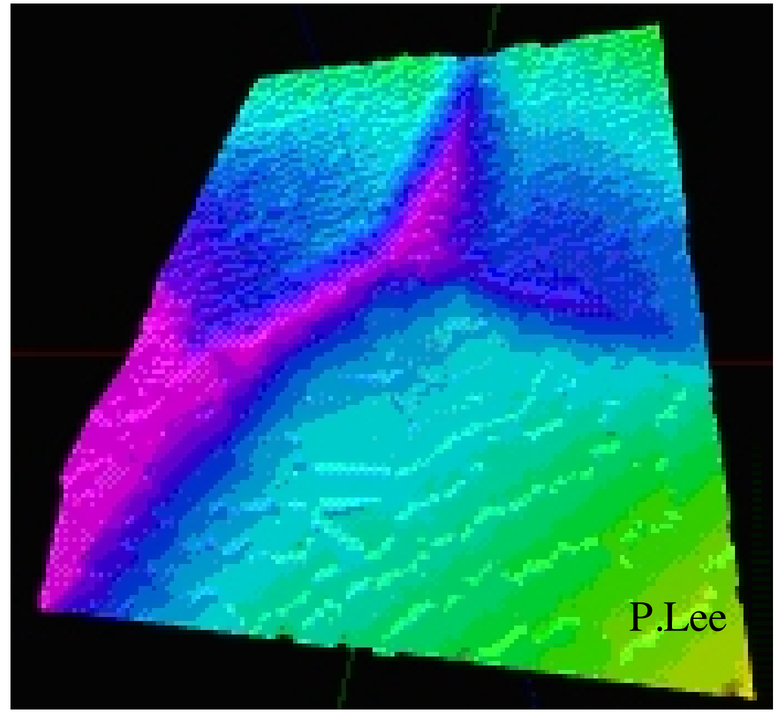




Some pictures

S.N.S. Eddy current scanner



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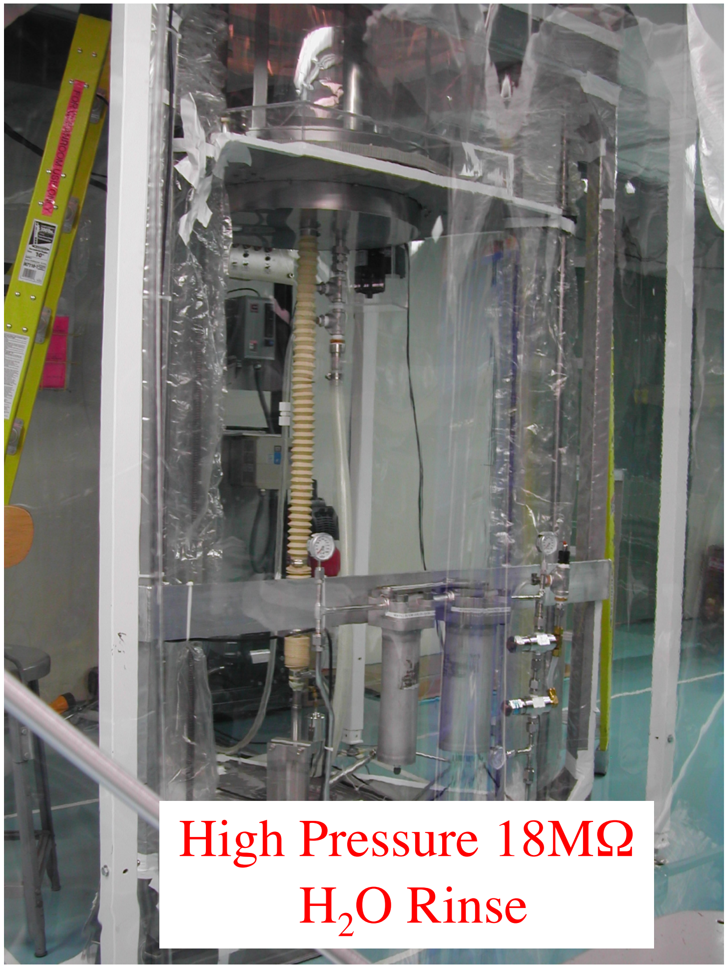
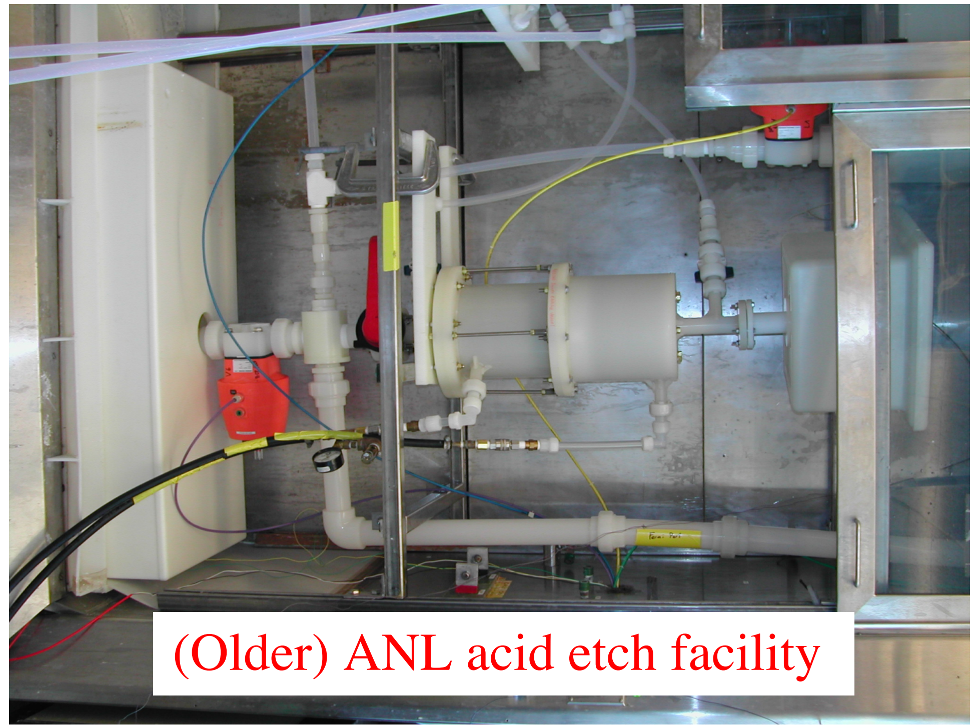
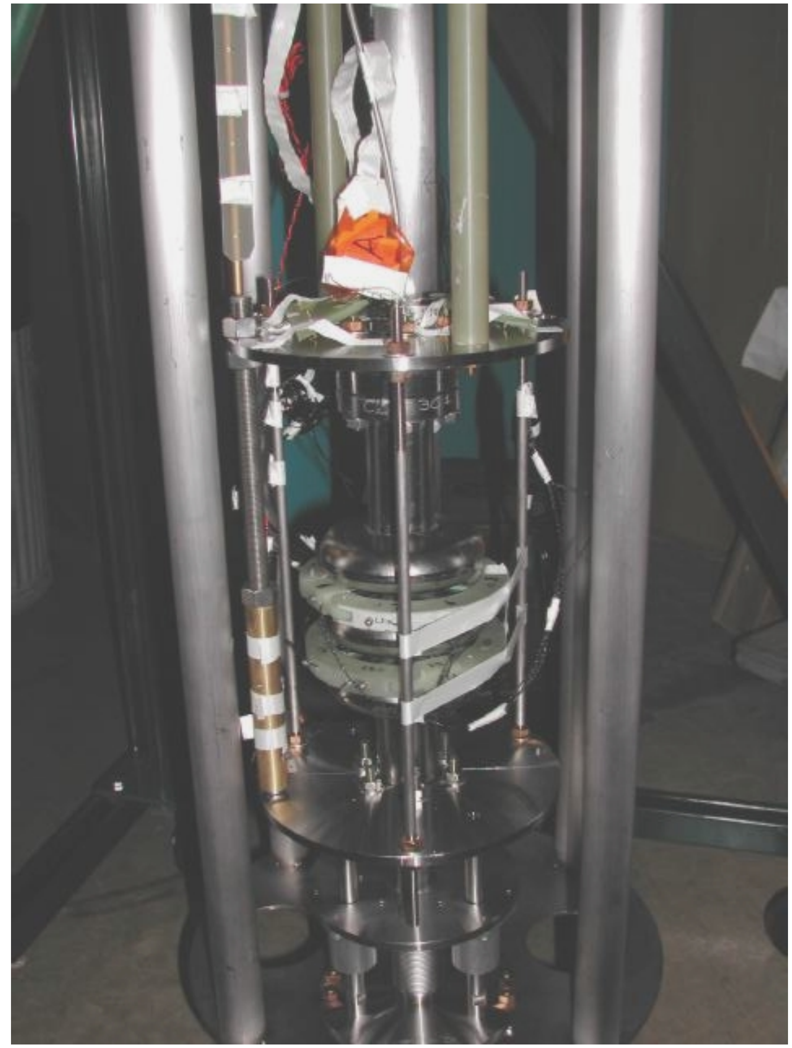


High Pressure 18MΩ H_2O Rinse



(Older) ANL acid etch facility

Some pictures



Details we haven't gotten into

- Ultrapure Nb; RRR and its measurement.
- Stamp, cut & weld (Nb is chewing gum, other schemes studied)
- EP or tumbling to smooth the interior
- Vertical test
- Power coupler, mechanical tuner issues, horizontal testing
- Piezo tuning for power
- 2nd sound to locate quenches
- Thermal modeling and cavity wall thickness
- RF phase & amplitude control